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Survival of the Greenest
Evolutionary economics and policies for energy innovation

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ABSTRACT

Evolutionary economics offers insights into the mechanisms that underlie innovations, structural changes and transitions, making it therefore of great value in framing policies aimed at environmental innovations and transitions to sustainable development. This paper identifies 'diversity', 'innovation', 'selection environment', 'bounded rationality', 'path dependency and lock-in', and 'coevolution' as the main concepts in evolutionary economics. These concepts are subsequently used to formulate guidelines for designing environmental policies. Here we have evaluated current Dutch policies related to energy technologies against this background and examined the development of three particular energy technologies within the adopted evolutionary economics framework, namely fuel cells, nuclear fusion, and photovoltaic cells. We conclude that in order to incorporate the core concepts of evolutionary economics, governmental technology policies should focus more on the *diversity* of technologies, strategies and businesses, rather than on economic efficiency as the key goal. Consequently, attention in strategic innovation policies should shift from outcomes to processes. It is interesting to note that evolutionary concepts conflicting with traditional growth theory are rarely incorporated in Dutch energy innovation policies.

Keywords: evolutionary economics; energy; environmental policy; innovation policy; sustainability; transition management

1 Introduction

Evolutionary economics was hinted at as early as 1900 in the question posed by Veblen (1898): 'Why is economics not an evolutionary science?'. Some decades later, Schumpeter and the Austrian school laid a fertile basis for the development of economics as an evolutionary science, notably by focusing on innovations. Schumpeter introduced the concepts of 'entrepreneur' and 'creative destruction' (Schumpeter, 1934, 1939, 1942), which came to have enormous influence in later economic policy-making. Evolutionary economics gained full momentum from the 1970s onwards, when Nelson and Winter (1982) built their theoretical framework on the evolutionary ideas laid down by Schumpeter. A number of evolutionary schools have evolved since, such as the evolutionary game theory, neo-Schumpeterian technology analysis and evolutionary multi-agent modelling.

Environmental policy, with its focus on innovations and system change, could greatly benefit from insights taken from evolutionary economics. In this paper, we aim to further this benefit by offering a theoretical evolutionary framework based on six central concepts: diversity, innovation, selection, bounded rationality, path dependency and lock-in, and *coevolution*. The evolutionary framework has been applied to Dutch energy innovation policies, for which environmental policy provides an important context (Sections 2 and 3). Distinguishing evolutionary elements in policy documents allows current energy innovation policies in the Netherlands to be evaluated from an evolutionary economics perspective (Section 4). The evolutionary concepts are tested on the technology level, with three main energy technologies being examined: fuel cells, nuclear fusion and photovoltaic cells (Section 5). Section 6 draws conlusions and makes a number of policy-relevant suggestions.

2 The evolutionary economic framework in six basic concepts

Evolutionary economics is increasingly regarded as a useful approach for assessing processes of structural change, including developments in technology, innovation, organisations, economic structure and institutions. The evolutionary perspective on economics replaces the traditional neoclassical assumption of rational and optimising behaviour with the more realistic assumption of bounded rationality of economic agents. The concept of *bounded rationality* implies that agents are not fully informed and will not include all possibilities in their considerations for performing any behavioural or economic act. Much more often, agents rely on routines, heuristics and experience. Bounded rationality is largely based on the idea that gathering full information is constrained by time and energy: it is simply impossible to collect all this information. Neither is it always useful to make a fully informed economic decision, since actions based on limited information usually offer a very satisfactory solution. Thus, a satisfactory outcome is often as good as or better than a perfect one, and it may be very rational in terms of costs related to achieving that solution (Vermeij, 2004). This concept of bounded rationality may take the form of routines, habits, imitation and a limited horizon in time and scale.

An important consequence of bounded rationality is heterogeneity in strategies of economic agents. This heterogeneity based on bounded rationality is contrary to the neoclassical economic approach, which usually involves a homogenous population of economic agents or strategies based on rational optimalisation. Heterogeneity translates into *diversity* of economic strategies, technologies, agents and structure. Diversity is a central concept in the evolutionary framework, as it is regarded as a measure for the fitness of an economic or ecological system. Fitness is in itself a measure of survival and reproduction in a system. Diversity relates to fitness through Fisher's Theorem: 'The greater the genetic variability upon which selection for fitness may act, the greater the expected improvement in fitness' (Fisher, 1930). The concept of diversity can be elaborated with three properties (Stirling, 2004): variety (the number of options in a portfolio), balance (the evenness of representation of the different options in the portfolio), and disparity (the degree to which the options in the portfolio are different from one another). All three dimensions will affect the outcomes of both innovation and selection.

Over time, system diversity will change as a result of the processes of innovation and selection. *Innovation* increases diversity in economic systems, analogous to mutation and re-combination in ecological systems. An increase in diversity implies an increase in opportunities for creative combinations contributing to the system's survival and fitness. Innovation is often the result of serendipity: an outcome that results from combining insight and expertise with chance (Fine and Deegan, 1996). Knowledge is thus crucial for processes of innovation, as these often involve re-combinations of existing techniques or concepts. Systematic search (R&D, science) is a method to increase the chance of useful innovative combinations.

Future visions and utopias may be useful for enhancing the effectivenes and focus in searching for profitable innovations. Innovations can be classified in various ways, for example, by distinguishing products, production and services. A common distinction is made between radical and incremental innovations. Incremental innovations are in line with the prevailing technological paradigm and often improve the performance of existing technologies. Incremental innovations usually reinforce the technological system they align with. Radical innovations, on the other hand, fall outside the prevailing technological paradigm and usually involve combinations of very different concepts and technologies. The 12th century windmill can be seen as a combination of waterwheel milling technology and sailing technology aimed at the use of wind energy (Mokyr, 1990: p. 44). Incremental innovations are far more common than radical innovations, but the influence of the latter can be enormous. A certain level of geographical or institutional isolation may be useful for harbouring radical innovations, that is, to allow for technological niches apart from the dominant technological regime. Iceland has recently put this notion into practice by developing a technological niche regime aimed at enhancing the concept of a hydrogen economy. Even in isolation, it should be noted that innovations are always developed within an institutional setting or innovation system and almost never in a linear fashion.

Diversity is reduced by processes of *selection*. Selection refers to the survival and reproduction of succesful agents or strategies in a system. A selection environment involves physical, physiological and geographical constraints, and in economic systems also technological, organisational, economic or institutional dimensions. Selection should not be simplified as 'survival of the fittest', but rather as the survival of the sufficiently adapted species in a changing selection environment. In a natural system, different species choose different survival strategies. A similar specialisation process applies to economic systems, where agents adapt their economic activities to the extent in which they can occupy their own niche in the economic system.

Repeated selection can result in *path dependencies*, which relates to increasing returns because of scale advantages, 'learning-by-using', imitation, network externalities, information effects (what is sold most is best known and thus sells more) and technical complementarity (Arthur, 1989). Increasing returns are often the result of and lead to positive feedback mechanisms. This process may end in the dominance of a particular technological or economic regime and may, in turn, be reinforced by incremental innovations based on previous innovations within that same regime. The situation where technologies become dominant due to positive feedback mechanisms is often referred to as *lock-in.* An often used example of a locked-in technology is the QWERTY keyboard. This keyboard is sometimes seen as lacking the efficiency of the 'Dvořák keyboard', but due to institutional and organisational embedding is still dominant, even though the original technological advantages based on the setting of the type bars in the typewriter are no longer relevant in computer keyboards. Processes of path dependency introduces history into economic dynamics, since technological developments tend to follow irreversible pathways. This is an important distinction from neoclassical economic theory, which suggests that a system can return to an optimal configuration, thus often neglecting technologically or institutionally irreversible developments. It should be noted that lock-in and path dependency make it particularly difficult to introduce and proliferate technologies outside the dominant technological regime. Reducing the chances of lock-in requires maintenance of diversity, and more generally, an extended level playing field (see Section 3).

A final core evolutionary concept is *coevolution*. This concept refers to the mutual influence and interference between two or more systems or populations: one system may exert selection pressure upon another system and vice versa, leading to related evolutionary developments in both systems. Coevolution is thus a particular concept of dynamic interaction between two populations with internal diversity. Norgaard (1984) first applied the concept of coevolution to socio-economic systems, introducing feedbacks between five partial systems of knowledge, values, organisation, technology and environment. Variations in each of these systems are strongly influenced by the other systems and vice versa. An example is the introduction of pesticides, which not only triggered higher crop yields and a policy effect, but also an increase in resistance of the pest to the vermin. Another example is the coevolution following the domestication of animals, which triggered not only large-scale cultural and economic changes in early societies, but also led to artificial selection of plants and animals (Campbell. 1996: p. 569). Later this was followed by a coevolution of human diseases and bacteria and viruses derived from animals (Diamond, 1997).

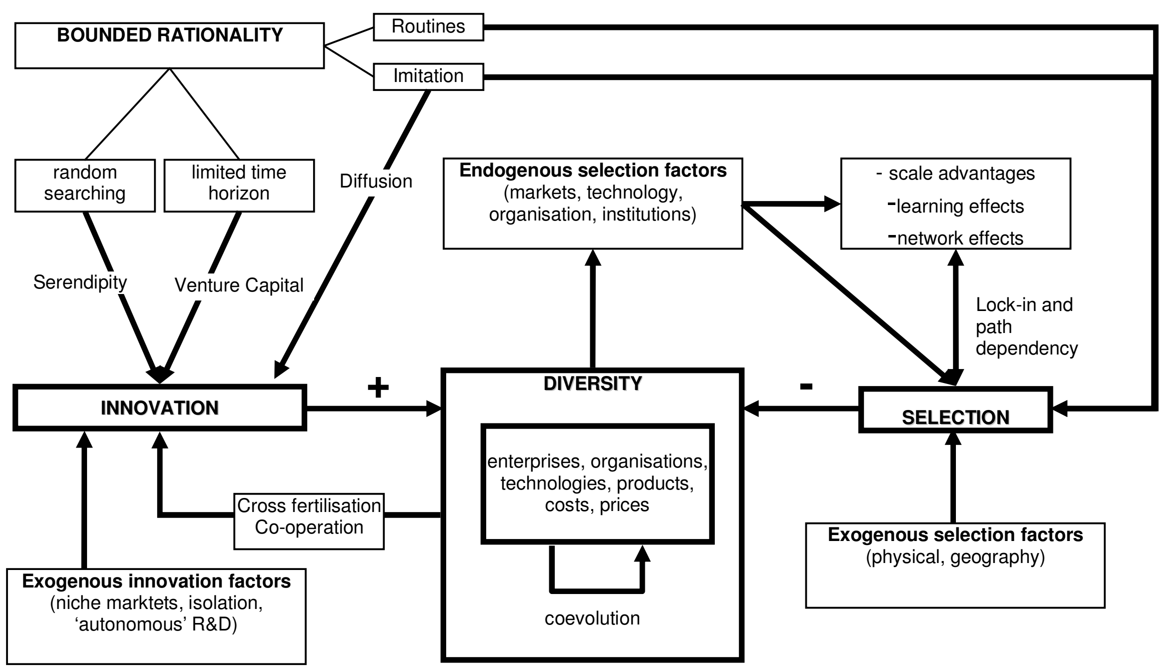


Figure 1 *A synthesis of the evolutionary concepts*

An example of coevolution between economic systems is provided by the heavy organic chemical industry in the United States, which was coal-based in the beginning of the last century. In the 1920s, the rapid growth in demand for petrol (gas) for automobiles in the United States supplied a large and inexpensive supply of olefins as a by-product in the refining process. By the end of WWII, the US chemical industry had fully changed to petroleum-based feedstocks (Ruttan, 2002). It is interesting to see that present-day sustainability policies sometimes refer to a new transition in the chemical sector, which should be based on biomass feedstocks. It may well be that changes in other economic systems are required in order to be able to make such changes in the chemical industry. Figure 1 synthesises the central evolutionary concepts and the interactions between them.

3 Evolutionary concepts and environmental policy

The evolutionary economic framework and its concepts give rise to new insights in the framing of environmental policy, particularly where this policy focuses on innovative solutions within the existing economic system or on system changes to sustainable development (also known as 'transitions' or 'industrial restructuring').

Although evolutionary processes are fundamentally without a goal or target, normative elements can be added by policy-makers. An important lesson of evolutionary economics is, however, that policy-makers should refrain from 'picking winners', since it can never be known beforehand what the winners will be in terms of economic, environmental or social benefits. Policy-makers could put evolutionary economics into practice by creating conditions under which evolutionary processes will lead to socially desirable outcomes. An evolutionary-based policy will focus on influencing the selection environment, promoting innovative strength, and making advantageous use of coevolution. An important element of an evolution-inspired policy is to promote diversity as a goal in itself.

A starting point for an evolutionary environmental policy lies in the concept of *path dependency*. It is of key importance to realise that most developments are decided in their early phases, and care is needed to foster new technologies and experiments in the early phases. It will still be important to keep an eye on all phases of an innovation or technology development. This is to maintain sufficient diversity technologies, from both the innovation (potential for combinations) and selection (acting upon diversity) perspectives. *Diversity management* should focus on stimulating a wide range of technologies and strategies in terms of variety, disparity and balance. Diversity of technologies and strategies introduces resilience and robustness in environmental policy, which goes beyond the concepts of efficiency and unilinear (economic) growth.

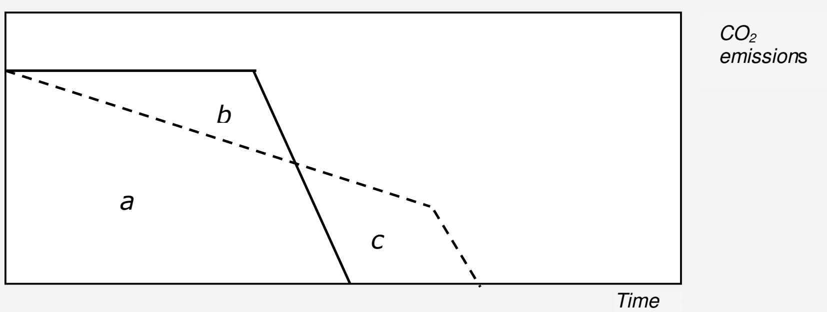
Diversity management requires an *'extended level playing field'*, where alternative technologies, organisations and institutions can compete with more dominant elements. A number of conditions needs to be met if a credible extended level playing field is to be realised. First, prices need to reflect all the external costs generated by activities and products. Secondly, technologies that are low on the learning curve, but at the same time may be expected to have large sustainability potential in the long run , need to receive special support, either by creating niches or by providing subsidies. Exposing such technologies to free market competition where short-term cost-effectiveness dominates is not a good strategy in trying to make a transition to long-term sustainability. An early lock-in of unsustainable technologies should therefore be avoided, as it will go along with an early decease of potentially attractive technologies (see the Box text for a theoretical example of this due to energy saving). A third condition for an extended level playing field is to try to expose different technological options to similar selection mechanisms.

Diversity increases through *innovation*. Innovation in evolutionary policy-making can be reinforced by increasing the chance of realising creative combinations, by stimulating attractive future perspectives, and by supplying capital and facilitation, through a level of niche management (i.e. increased isolation) and by increasing insight and knowledge. The concept of serendipity could become operational through the creation of innovative networks, with a focus on cross-fertilisation and stimulation. Such cross-fertilisation from different institutional systems may also lead to fruitful *coevolution*. An example is applying our experience from natural gas systems to set up distribution systems in the hydrogen economy. Isolated experiments and initiatives on the other hand may yield unique and surprising technological pathways outside the dominant regime. Such initiatives may be useful in small-scale incubator settings, where experiments are fostered as possible contributors for future solutions.

Box: Evolutionary assessment of energy saving

The notions of lock-in and environmental policy may be illustrated by experiences from energy-saving policy. Energy-saving strategies often imply an increased efficiency of the use of fossil fuels. There are two different types of energy-saving strategies: **(1)** one decreasing the demand for useful energy (e.g. insulating homes or decreasing the air resistance of cars) and **(2)** the other increasing the efficiency of converting fossil fuels into useful energy. A decreased demand for useful energy will not alter the economic advantage of one fuel over the other. An increased conversion efficiency of fossil fuels, however, will decrease the costs per unit of useful energy based on fossil fuel, and thereby strengthen the economic advantage and lock-in of these fuels. Consequently, the increased conversion efficiency of fossil fuels could hamper the transition towards an energy system based on more sustainable energy resources.

This point is illustrated in the following graph:



The solid line shows CO_2 emissions due to a large-scale transition to sustainable energy production, while the broken line shows CO_2 emission in an energy-savings scenario. Cumulative emissions in the transition scenario are *a+b*. Cumulative emissions in the energy-saving scenario are *a+c*. The most attractive scenario (in terms of reductions) depends on whether *b>c* or *b<c*. Now, if time before the point of transition increases, *b* increases compared to *c*, thus making energy savings more attractive. On the other hand, since the saving of energy is progressing well (especially in the initial stages of this scenario), policies for rendering a transition may become less interesting. Energy-saving may hamper the sense of urgency that is often considered necessary for a transition to sustainable energy production.

This point pits a theoretical argument against energy-saving policies. In practice, however, it is conceivable to elaborate a more diverse and sophisticated policy strategy, aimed at a sustainability transition in the longer term, but to maintain energy-saving policies in the shorter term. This may not be the most cost-effective approach, but it does line up with the theoretical perspectives from the evolutionary economic theory and thus yields a more diverse and robust economy.

It is crucial for evolutionary policy-makers to balance between diversity and selection, so as to prevent a system ending up in either deadlock or inefficiency. Here, it is important to balance the cost of diversity in the short term against the benefits of diversity in the longer term. This trade-off can never be made on the basis of full information, but relies on expert estimation of chances, barriers and opportunities. On a larger scale – e.g. Europe as compared to any one of its countries – it may be easier to balance between diversity and efficiency, since relatively minor technologies may also reach a minimal scale advantage at this level. With this insight, policy-makers should be invited to align trajectories for sustainable development in large-scale co-operation, such as in the EU Framework programmes.

It is important to note that evolutionary theory does not offer an 'optimal policy'. *Bounded rationality* prevents economic agents from optimising their economic behaviour. An implication for evolutionary theory is that pricing instruments will not even realize efficiency at the level of individual agents. The efficiency – and effectiveness – of such instruments is therefore overestimated in traditional economic analysis and policy-making.

4 Assessment of Dutch energy innovation policy from an evolutionary perspective

Design of the Dutch energy innovation policy

Dutch policies concerning the stimulation of energy innovations are embedded in several policy fields with different co-ordinating ministerial departments. The Ministry of Economic Affairs is responsible for energy policy and innovation policy. Climate policy, transition policy and the stimulation of environmentally sound technologies are co-ordinated by the Department of the Environment within the Ministry of Housing, Spatial Planning and the Environment. Consequently, recent policies on the stimulation of energy innovation are based on many different memoranda and reports formulated by different ministries and advisory bodies. The evolutionary economic assessment of energy innovation policy in the Netherlands is based on an analysis of the objectives and mechanisms identified in these reports. In our paper we will only refer to the dominant reports for current policies: 'Energy Research Strategy' (Ministry of Economic Affairs, 2001) and 'Action for Innovation' (Ministry of Economic Affairs, 2004a).

Policies to stimulate energy innovations relate to the overall objectives of energy policy, which are largely inspired by the Kyoto Protocol objectives. The Dutch CO_2-emission reduction goals are translated into objectives to stimulate energy savings and the use of sustainable ('green') energy resources. An important point of departure for the Energy Research Strategy is the changing position of the government: 'The government's role is shifting from a player in the field to a conductor. The character of policy instruments is also changing: demand is influenced by instruments such as norms, standards and fiscal investment incentives. Furthermore, a more generic approach is more consistent with contemporary thinking. New approaches, such as the use of technology roadmaps, have become established. The focus of existing instruments is shifting, for example, towards dissemination of knowlegde and issues such as public acceptance' (Ministry of Economic Affairs, 2001).

'Action for innovation' (Ministry of Economic Affairs, 2004a) elaborates the policy focus for improving a sustainable economic growth through innovation. It presents the plans by the Dutch government to 'tackle the Lisbon ambition'. This ambition was formulated at the European Council in Lisbon (2000) where the member states agreed that the European Union should develop into the most competitive and dynamic knowlegde-based economy in the world within ten years.[1] 'Action for innovation' was preceded by a number of reports and memoranda which agreed on the perceived problems: (1) the Dutch innovation climate is not attractive enough; (2) this climate lacks innovative companies and (3) research lacks sufficient focus and quantity. Currrent Dutch innovation policy is based on the concept of a dynamic innovation system: the connection between the development, application and introduction of innovations to the market. It focuses on improving the weak spots in the system: the knowlegde infrastructure and the introduction of innovations on the market. Current innovation policy proposes the development of generic instruments to deal with these problems. Specific attention is also paid to focusing on the economic sectors that are frontrunners, so as to make full use of the advantages of the cutting-edge industries (Ministry of Economic Affairs, 2004a). Thus the Dutch innovation policy has two main goals: to improve the *focus* on the strengths of the innovation system and to increase the *mass* of the innovation system as a whole.

Evolutionary assessment of Dutch energy innovation policy

The identified evolutionary economic concepts of diversity, innovation, selection, bounded rationality, path dependency (and lock-in), and coevolution can be used for a policy assessment, as seen in our analysis of a number of key documents of Dutch energy innovation policy (see Appendix A for the list).

Although the point of departure of current Dutch innovation policies is a systems approach, which is in line with evolutionary economic thinking, the practical implementation of these policies still focuses on traditional policy instruments, such as subsidies, fiscal measures and negotiated agreements.[2] Only very recently an increase comes forth in focus on and tentative application of system instruments, such as innovation networks and thematic innovation programmes. Specifically, thematic public–private partnerships in R&D based at the large Dutch technological institutes are generally conceived to be very well organised (OECD, 2003).

Many of the central evolutionary concepts can be traced to energy innovation policy, although practical application is in many instances limited. For example, strategic documents signal the importance of *diversity* and diversity management, but this management is more applicable to technologies than strategies, sectors or companies. A central point in innovation policy is the dilemma between focus and momentum, on the one hand, and diversity, on the other. This is much in line with the theoretical dilemma introduced in the previous section.

The elaboration of evolutionary principles behind the concept of *innovation* shows a somewhat mixed assessment. Much attention is paid to interaction and technology transfer, which is often regarded as one of the main shortcomings in the Dutch innovation system. On the other hand, elements like cross-fertilisation, serendipity, isolation and niche markets do not receive any attention in energy innovation policy. Increase in the fundamental body of knowledge is largely dependent on training and education, both of which receive considerable attention in policy issues. Finally, we discern a large focus on technologies, or rather, organisational or institutional innovations, which may be just as important for goals of productivity.

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1 See Presidency Conclusions of the Lisbon European Council (2000): http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/ec/00100-r1.en0.htm

2 Although negotiated agreements (also called voluntary agreements or covenants) are not common in all countries, they have flourished in the Netherlands since the 1980s. These are agreements between government and private parties for reaching targets on the reduction of environmental pressure. They often act as an alternative to direct regulation. Negotiated agreements are based on trust between the parties involved, but have no foundation in public law. Part of the arrangement is usually that legislative measures are either not imposed or imposed at a later stage (Hofman and Schrama, 2003).

The evolutionary concept of *selection environment* is lacking. In Dutch energy innovation policy the market is implicitly considered to be the dominant selection factor, to which government should maintain a sound distance so as not to disturb the mechanisms of the free market. Relatively much attention is reserved for the removal of innovation barriers. Much policy is focused on the inclusion of external costs, which should, to a large extent, be sufficient for making market mechanisms work properly. 'A new selection mechanism for innovations in the free market can thus be applied; government does not need to interfere, as the winners will come forward automatically' (Ministry of Economic Affairs, 2004b).

With regard to the concept of *bounded rationality,* much attention is given to the elements of time horizon and imitation. A limited time horizon can be associated with many private entrepreneurs. Government itself often includes more far-reaching time horizons, for example, by making use of scenario studies and strategic planning tools. On the other hand, a level of routine can often be distinguished in the application of traditional policy instruments focused on direct economic incentives, such as subsidies and taxes. Imitation increasingly plays a role in the framing of innovation policies, especially for SMEs following frontrunning enterprises.

The concepts of *path dependency* and *lock-in* have found their way in strategic policy, including the concept of the extended level playing field. Elaboration of the strategic concepts into operational policy instruments seems to be turned toward prevention of barriers, rather than stimulation of driving forces. The prevention of lock-in – which is very clearly incorporated in policy – is thus mainly framed in postponing selection, rather than full-hearted support for flexible solutions. A discussion on more strategic choices for the prevention of lock-in may be useful in energy policy, for example, in large-scale versus small-scale energy production. The dense energy network in the Netherlands is only tentatively mentioned, supports a policy choice for large-scale and centralised options rather than small-scale solutions. Finally, the element of level playing field is very often mentioned, but usually in the context of competitive relations with other countries with a much more limited meaning than proposed in the previous section. Different positions on the learning curve are not recognised as an important point of attention. The concept of *level playing field* is not usually regarded in its extended version, i.e. where alternative technologies, organisations and institutions can compete with more dominant elements.

Finally, the concept of *coevolution* is not generally used as an important element in Dutch innovation policies. Although different memoranda on the subject of energy innovation note the importance of developments in non-energy-related technologies, there is hardly any connection between energy policy and innovation policy. Coevolution is, moreover, seen as an advantageous or unpleasent coincidence but not something policy could conciously try to stimulate.

From this assessment, we may conclude that the evolutionary economic concepts that are adopted in policy are in accordance with traditional notions of efficiency and effectiveness: diversity of technologies, co-operation in public-private partnerships, application of future visions for roadmapping, market as a selective mechanism, several elements of bounded rationality and the consciousness of scale advantages. The concepts that are applied most thus satisfy both evolutionary and traditional perspectives. Practical operation of the strategies usually still relies on traditional market instruments, which do not necessarily collide with the evolutionary perspective; however, we can see a tendency towards the application of system instruments, which align well with evolutionary policy-making.

5 Evolutionary assessment of three specific energy technologies

Fuel cells

Fuel cells are clean and efficient energy transformation appliances, which convert a fuel (usually hydrogen) into electricity (and heat). In general discussions, fuel cells are often related to the 'hydrogen economy'. In this concept, hydrogen is the central energy carrier and fuel cells are an important element of the system. We can attribute a high level of *diversity* in techniques, applications and companies involved thanks to fuel cells. With regard to the *innovation* aspects, fuel cells can be considered a radical innovation, characterised by strong interactions between different industries (*inter alia* the chemical industry, energy companies and car manufacturers). Niche markets can be found in aeronautics and ('zero emission') motor vehicles. Liberalisation of energy markets (provided that there is a level playing field) and stringent environmental policy might be conducive to creating a favourable *selection* environment for fuel cells. *Bounded rationality* could hamper the introduction of fuel cells, as it requires a clean break with existing routines and long-term, risky investments. Nevertheless, if one sheep leaps over the ditch, the rest will follow (we can already observe this imitative behaviour among car manufactureres, many of whom are now working on fuel-cell cars). *Path dependency and lock-in* in existing technologies (such as the internal combustion engine and batteries) imply an important barrier for fuel cells. On the other hand, economies of scale in the application of fuel cells are limited, which means that they would fit very well into small-scale, decentralised energy systems. In terms of *coevolution,* a strong interdependence between fuel cells and other components of the energy system can be noted (such as the fuel supply infrastructure).

The Dutch as well as the larger European fuel-cell arena is still very much focused on the R&D phase, since large-scale commercial application is still beyond the horizon. Many technical and economic barriers remain to be overcome. However, small niche markets are already in place, often in hybrid applications. Increasing demand for fuel cells may now be at the turning point of opportunity: further new applications will be increasingly important, so as to allow the technology to move forward on the learning curve. Government may play a role here, both as legislator and large customer.

Photovoltaic cells (PV)

Photovoltaic (PV) or solar cells are seen in sharp contrast to nuclear fusion in the sense that the first type of energy production is conceptually very de-centralised. The silicon-based PV cell was discovered more or less by accident in the electronics industry, making it a good example of serendipity. The concept of applying thin film cells originated in photography, providing a good example of cross-fertilisation. Niche markets for PV applications, first developed in aerospace technology, were later extended to off-grid applications such as marine light beacons. PV applications may be grid-coupled, although there is no fundamental need to do so. Scale advantages in application are very limited. Many off-grid applications in remote areas, for example, are conceivable or already in place. Investment costs are, however, still very high, even though the learning curve is proving to be rapid, very much due to learning-by-doing experiences. Large-scale application opportunities in the Netherlands are seen as being limited, since the Dutch electricity network is very dense, thus not allowing for many off-grid niche markets. Large-scale application in other parts of the world will certainly require a break in the technological regime, as the PV production units can be applied in a much more decentralised context than present power production units.

In addressing PV in terms of the six evolutionary-economic aspects, we can make the following observations. *Diversity* is high in several respects: companies dealing with PV-technology display a large variety (both in size and type of industry); a number of different technologies are in existence, in addition to the 'traditional' monocrystalline silicon cells, and there is a wide range of (potential) areas of application. With respect to *innovation*, we saw that serendipity, cross-fertilisation and niche markets have played an important role in the development of PV. On the other hand, the lack of an authoritative, coherent future perspective on the role of PV may have been a restraining factor.[3] In the *selection* environment for PV, government policies form an essential factor. PV is still an expensive technology and will remain dependent on subsidies and other preferential policy measures for quite some time. Among the elements of *bounded rationality*, it is the short-time horizons of private investors that stand out. PV is capital intensive, with a long lifetime and low operational costs. Its financial performance is therefore highly dependent on the discount rate or payback period applied by the investor.As far as the *path-dependency and lock-in,*, we can mention that because PV can hardly benefit from economies of scale in application, it is therefore particularly suitable for systems of decentralised electricity supply. Finally, with respect to *co-evolution* a relevant feature of PV is its intermittent character (due to the fluctuations in solar energy influx). This implies that application of PV application will have implications for other components of the energy system (such as energy storage devices).

Nuclear fusion

The path of nuclear fusion to commercial application has long been said to be about 50 years and remains so to date. Much research is still very fundamental and projects on application are very much focused on experimenting with fundamental principles. The high costs involved and the still distant benefits largely exclude private partners from the research. The very centralised energy technology only allows for very large-scale units. Present-day experimental units are thus very expensive. Even though commercial application may still be beyond the horizon, the learning curve is passing very fast, even when compared to the well-known Moore's Law for the evolution of computer processors (Figure 2).

The high costs involved in this nuclear fusion allow for only one type of fusion technology, the one based on Tokomak installations. A second important element is the high level of co-operation, illustrated by the continous interaction between the United States and the Soviet Union even during the Cold War period. Finally, the vision on the future is very utopian in attractiveness: large-scale application of nuclear fusion requires cheap, unlimited and widely availabe fuel (water) and causes hardly any environmentally harmful emissions. All these features allow for a fast learning curve for nuclear fusion.

Asessing nuclear fusion for the six evolutionary economic aspects that we have distinguished, it is obvious that the degree of *diversity* in this technology is very low. The main observation concerning the factors relating to *innovation*, is that there is a lot of (worldwide) co-operation within a relatively small network of experts, whose interactions with other sectors are limited. There are, as yet, no (niche) markets for the technology, of which the viability will be strongly dependent on a favourable *selection* environment, in which stringent CO_2 policies will have to play an important role. With respect to *bounded rationality,* it can be said that there is a lack of interest among private investors (due to the long time horizon involved) and an absence of established routines on which to base the technology's application. With respect to p*ath dependency and lock-in,* the huge investments in fusion technology would clearly seem have an irreversible character and economies of scale are extremely important. This implies that nuclear fusion will fit in well to the existing large scale electricity supply regime, but it is incompatible with a decentralised energy supply system. Regarding *coevolution,* there is very little exchange to be noted with other areas of energy technology, but some complementarity between areas of expertise relevant for nuclear fusion can be observed (e.g. plasma physics and materials science).

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[3] To some extent, the publication in September 2004 by the European Commission of 'A Vision for Photovoltaic Technology for 2030 and Beyond' may have filled this gap.
See: http://europa.eu.int/comm/research/energy/photovoltaics/introduction_en.html

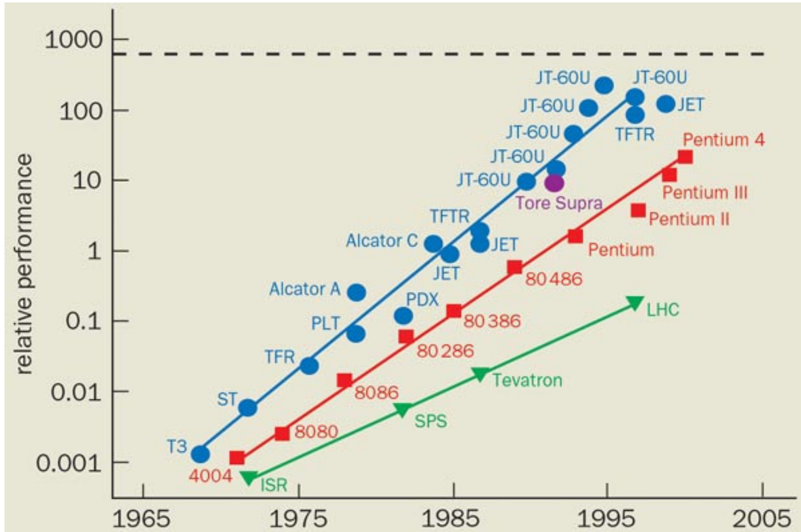

Figure 2 Fusion experiments have kept pace with other hi-tech developments over the last 30 years. Since the early Russian T3 tokamak, the performance of fusion plasmas has doubled every 1.8 years (blue line). The performance of fusion plasmas is defined in terms of the triple product (density × temperature × time). This triple product compares favourably with the doubling of the energy of particle accelerators every 3 years (green line), and the doubling of the number of transistors on a chip every 2 years (red line). The dashed line at the top shows the performance expected with ITER (Source: Hoang and Jacquinot, 2004).

6 Conclusions

Evolutionary economics offers clear insights into the mechanisms that underlie innovations, structural changes and system transitions, therefore making it highly valuable for the framing of policies aimed at fostering environmental innovations and a transition to sustainable development. On the basis of major literature sources in this field, we have drawn up a list of core concepts which can be helpful in putting the evolutionary economic theory into policy practice. The central evolutionary concepts include 'diversity', 'innovation', 'selection environment', 'bounded rationality', 'path dependence and lock-in', and 'coevolution'. Here, we have presented an evolutionary economics assessment of current Dutch policies on energy innovations, showing that some evolutionary economic notions have found their way into the policy discourse. Nevertheless, when it comes to concrete actions, only those aspects of evolutionary economic theory that do not conflict with notions of efficiency are put into practice. Current policies concentrate on cooperation, education, future perspectives and demonstration projects. Evolutionary aspects such as innovative combinations, cross-fertilisation and serendipity, however, are not stimulated and sometimes even hampered by current policies. Moreover, the idea of an extended level playing field receives hardly any attention.

The case studies of three specific energy technologies – fuel cells, nuclear fusion and photovoltaic cells (PV) – show how useful evolutionary economic notions are in understanding the development of new technologies. The development of fuel cells has been stimulated by a high degree of diversity of economic agents, techniques and products, by the cooperation between different parties, and by the niche market (e.g. for zero-emission cars). The case of nuclear fusion shows the importance of having an appealing perspective of a clean and inexhaustible energy source. However, in spite of this positive future perspective, it is not enough to overcome the bounded rationality of private investors. Photovoltaic cell technology, on the other hand, has developed well in the Netherlands despite the drawback of a pessimistic future perspective. This case study showed both the important role of serendipity and cross-fertilisation, and of niche markets, for the development of this technology.

Although a central concept of evolutionary processes the inherent absence of a purpose or goal, this does not mean that it is impossible to influence these processes. Since it is impossible to predict which technologies will be the ‘greenest’ or ‘best’ in any other way, policy-makers should refrain from ‘picking winners’. Instead, policy aimed at stimulating the development of sustainable technologies should emphasise the creation of conditions under which only the greenest technologies will survive.

References

Arthur, B., 1989. Competing technologies, increasing returns, and lock-in by historical events. Economic Journal 99: 116-131.

Campbell, N.A., 1996. Biology. 4th edition. The Benjamin/Cummings Publishing Company, Menlo Park CA.

Department of Economic Affairs, 2004a. Action for innovation; Tackling the Lisbon ambition. The Hague

Department of Economic Affairs, 2004b. Innovation in energy policy. Dept. Economic Affairs, The Hague.

Diamond, J., 1997. Guns, Germs and Steel: The Fates of Human Societies, W. W. Norton, New York.

Fine, G., and J. Deegan, 1996. Three principles of serendipity: insight, chance and discovery in qualitative research. International Journal of Qualitative Studies in Education 9 (4): 434-447.

Fisher, R.A., 1930. The Genetical Theory of Natural Selection. Clarendon, Oxford.

Hofman, P. S. and G. J. I. Schrama, 2003. Environmental policy and environment-oriented technology policy in The Netherlands. In: Schrama, G. J. I. and S. Sedlacek (Ed.), Environmental and technology policy in Europe, technological innovation and policy integration. Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 125-162.

Ministry of Economic Affairs, 2001. EOS; Energy Research Strategy. The Hague

Mokyr, J., 1990. The lever of the riches: technological creativity and economic progress. Oxford University Press, Oxford.

Nelson, R., and S. Winter, 1982. An Evolutionary Theory of Economic Change. Harvard University Press, Cambridge MA.

Norgaard, R.B., 1984. Coevolutionary development potential. Land Economics 60: 160-173.

OECD, 2003. Public-private partnerships for research and innovation: an evaluation of the Dutch experience. OECD, Paris.

G.T. Hoang and J. Jacquinot, 2004. Controlled fusion: the next step. Physics World, January 2004. http://physicsweb.org/articles/world/17/1/6/1#pwhoa4_01-04

Ruttan, V., 2002. Sources of technical change: induced innovation, evolutionary theory and path dependence. In: Grübler, A., N. Nakicenovic and W. D. Nordhaus (Eds.) Technological Change and the Environment. IIASA, Laxenburg, pp. 9-39.

Schumpeter, J.A., 1934. The Theory of Economic Development. Harvard University Press, Cambridge MA.

Schumpeter, J.A., 1939. Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process (2 vols). McGraw-Hill, New York.

Schumpeter, J.A., 1942. Capitalism, Socialism and Democracy. Harper and Brothers Publishers, New York.

Stirling, A., 2004. Diverse designs, fostering technological diversity in innovation for sustainability. Paper presented at conference 'Innovation, Sustainability and Policy', Seeon (Germany), 23-25 May 2004

Veblen, T., 1898. Why is economics not an evolutionary science? Quarterly Journal of Economics 12 (4): 373-397

Vermeij, G., 2004. Nature, an economic history. Princeton University Press, Princeton NJ.

APPENDIX 1: KEY DOCUMENTS OF DUTCH ENERGY INNOVATION POLICY

In Dutch; includes several background documents

AWT, 2003. Netwerken met kennis, kennisabsorptie en kennisbenutting door bedrijven. Adviesraad voor Wetenschap en Technologie (advies 56), Den Haag

AWT, 2004. Tijd om te oogsten, vernieuwing in het innovatiebeleid. Adviesraad voor Wetenschap en Technologie (advies 59), Den Haag

CPB, Rathenau Insituut, RIVM-MNP, RPB en SCP, 2003. Investeren in kennis, een maatschappelijk-economische beoordeling van de BSIK-projecten. CPB, Den Haag.

EZ, 1974. Energienota. Tweede Kamer 1974-75 (13 122 nrs. 1-2), Den Haag

EZ, 1979. Nota Energiebeleid. Tweede Kamer (15802, nrs. 1 en 2), Den Haag

EZ, 1990. Nota Energiebesparing. Tweede Kamer (21570, nrs. 1 en 2), Den Haag

EZ, 1993. Vervolgnota Energiebsparing. Tweede Kamer 1993-94 (23 561, nrs 1-2), Den Haag

EZ, 1995. Kennis in beweging. Tweede Kamer (Bijlage bij 24229, nr. 1), Den Haag

EZ, 1996. Derde Energienota. Tweede Kamer (24525, nrs. 1-2), Den Haag

EZ, 1997. Duurzame energie in opmars. Actieprogramma 1997-2000. Ministerie Economische Zaken, Den Haag

EZ, 1999a. Industrie- en dienstenbeleid. Tweede Kamer (26628, nr. 1), Den Haag

EZ, 1999b. Energierapport 1999. Ministerie Economische Zaken (publicatie-nummer 13-B-65)/ Tweede Kamer (26898 no. 1), Den Haag

EZ, 2000a. De Kenniseconomie in Zicht, De Nederlandse invulling van de Lissabon Agenda voor 2001. Tweede Kamer (27406, nr. 2), Den Haag

EZ, 2000b. Energie en samenleving in 2050, Nederland in wereldbeelden. Ministerie Economische Zaken, Den Haag

EZ, 2001. Nota Energie Onderzoek Strategie (EOS). Ministerie Economische Zaken (publicatienummer 01ME14)/ Tweede Kamer (28108, nr. 1), Den Haag

EZ, 2002. Energierapport 2002, investeren in energie, keuzes voor de toekomst. Tweede Kamer (28241, nr. 2), Den Haag

EZ, 2003a. Rapport Implementatie EOS. Ministerie Economische Zaken, Den Haag, februari 2003

EZ, 2003b. Innovatiebrief: In actie voor innovatie. Nota 'De kenniseconomie in zicht'. Tweede Kamer (27406, nr. 4), Den Haag

EZ, 2004a. Innovatie in het Energiebeleid. Energietransitie: stand van zaken en het vervolg. Ministerie Economische Zaken, Den Haag

EZ, 2004b. Industriebrief: Hart voor industrie. Ministerie Economische Zaken, Den Haag

EZ en VROM, 1991. Technologie en milieu, technologie als schakel tussen ecologie en economie. Ministeries Economische Zaken/Volkshuisvesting, Ruimtelijke Ordening en Milieu, Den Haag

IBO, 2002. Samenwerken en stroomlijnen: opties voor een effectief innovatiebeleid. Eindrapportage Interdepartementaal Beleidsonderzoek (EZ-02-311), Den Haag

OC&W, 2003. Wetenschapsbudget 04. Tweede Kamer (29338, nr. 1), Den Haag

SER, 2003. Interactie voor Innovatie. Advies 03/11. Sociaal Economische Raad, Den Haag

Tweede Kamer, 2004. Nota 'De kenniseconomie in zicht': Voortgangsbrief van de Minister-President. Tweede Kamer (27406 nr. 26), Den Haag

VROM, 1990. Nota Klimaatverandering. Tweede Kamer (22232 nrs. 1 en 2), Den Haag

VROM, 1999. Uitvoeringsnota Klimaatbeleid. Ministerie Volkshuisvesting, Ruimtelijke Ordening en Milieu, Den Haag

VROM, 2001. Een wereld en een wil, werken aan duurzaamheid – Nationaal Milieubeleidsplan 4. Ministerie Volkshuisvesting, Ruimtelijke Ordening en Milieu, Den Haag

VROM, 2002. Evaluatienota Klimaatbeleid, De voortgang van het Nederlandse klimaatbeleid: een evaluatie bij het ijkmoment 2002. Tweede Kamer (28240 no. 2), Den Haag

VROM-Raad, 2002. Milieu en economie: ontkoppeling door innovatie. VROM-Raad (advies 036), Den Haag